NAVAL POSTGRADUATE SCHOOL
MONTEREY, CALIFORNIA

THESIS

COMPARISON OF LIDAR AND MINI-RAWIN SONDE PROFILES

by

Daniel E. Harrison

June, 1998

Thesis Co-Advisors: Kenneth L. Davidson
Carlyle H. Wash

Approved for public release; distribution is unlimited.

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE June, 1998	3. REPORT TYPE AND DATES COVERED Master's Thesis

4. TITLE AND SUBTITLE
COMPARISON OF LIDAR AND MINI-RAWIN SONDE PROFILES

5. FUNDING NUMBERS

6. AUTHOR(S) Daniel E. Harrison

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Postgraduate School
Monterey CA 93943-5000

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(maximum 200 words)*

Current Light Detection and Ranging (LIDAR) technology allows for remotely sensed, real-time measurement of most atmospheric properties including structure, dynamics and primary chemical constituents. The LIDAR Atmospheric Profile Sensor (LAPS) instrument, completed in April 1996 at the Applied Research Laboratory/Pennsylvania State University (ARL/PSU), was developed as a prototype sensor for continuous, automated atmospheric soundings aboard aircraft carriers, advanced-radar combatants and shore stations. These data can then be used to calculate the atmospheric refractivity profiles for electromagnetic propagation prediction and as input to system performance assessments.

This report shows the advantages and disadvantages of LAPS atmospheric data as compared to the MRS sounders currently in use. LAPS can provide an accurate, continuous on-demand real-time data, is able to characterize variations in the marine boundary layer, and does not require cumbersome logistic support (e.g. helium bottles and balloons). The present weaknesses of LAPS are its relatively coarse vertical resolution, degraded daytime data due to scattering, sometimes erratic temperature measurements, and ship's gas absorption.

14. SUBJECT TERMS Environmental Data, Radio Physical Optics, Radar Performance Prediction, Radiosonde, Refraction, Rocketsonde, SHAREM 110, Surface Based Duct

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18 298-102

Approved for public release; distribution is unlimited.

COMPARISON OF LIDAR AND MINI-RAWIN SONDE PROFILES

Daniel Edward Harrison
Lieutenant Commander, United States Navy
B.S., United States Naval Academy, 1985

Submitted in partial fulfillment
of the requirements for the degree of

MASTER OF SCIENCE IN METEOROLOGY AND PHYSICAL OCEANOGRAPHY

from the

NAVAL POSTGRADUATE SCHOOL
June 1998

Author: ______________________________
Daniel E. Harrison

Approved by: ______________________________
Kenneth L. Davidson, Thesis Co-Advisor

____
Carlyle H. Wash, Thesis Co-Advisor

____
Carlyle H. Wash, Chairman
Department of Meteorology

ABSTRACT

Current Light Detection and Ranging (LIDAR) technology allows for remotely sensed, real-time measurement of most atmospheric properties including structure, dynamics and primary chemical constituents. The LIDAR Atmospheric Profile Sensor (LAPS) instrument, completed in April 1996 at the Applied Research Laboratory/Pennsylvania State University (ARL/PSU), was developed as a prototype sensor for continuous, automated atmospheric soundings aboard aircraft carriers, advanced-radar combatants and shore stations. These data can then be used to calculate the atmospheric refractivity profiles for electromagnetic propagation prediction and as input to system performance assessments.

This report shows the advantages and disadvantages of LAPS atmospheric data as compared to the MRS sounders currently in use. LAPS can provide an accurate, continuous on-demand real-time data, is able to characterize variations in the marine boundary layer, and does not require cumbersome logistic support (e.g. helium bottles and balloons). The present weaknesses of LAPS are its relatively coarse vertical resolution, degraded daytime data due to scattering, sometimes erratic temperature measurements, and ship's gas absorption.

TABLE OF CONTENTS

ACKNOWLEDGMENT

The author wishes to thank Professor C.R. Philbrick and Dr. D. Lysak, Pennsylvania State University, for providing the LIDAR data and their guidance on LIDAR issues and patience during the period of this study. In addition, he also wants to thank Ms. Jordan, Naval Postgraduate School for her assistance in processing the data evaluated in this study, and the MET Teams from NLMOC Norfolk and NLMOF Jacksonville for launching the rawinsondes and processing data.

I. INTRODUCTION

Naval operations are becoming more dependent on the performance of extremely sensitive combat systems, sensors and weapons which are highly influenced by atmospheric conditions. In particular, sophisticated electromagnetic (EM) sensors are designed to exploit atmospheric propagation effects within narrow frequency windows, and thus are extremely dependent on atmospheric refractive parameters.

A critical component in providing realistic atmospheric propagation conditions for predicting system performance is a timely, high-resolution vertical profile of the radar refractive index. Realistic and accurate range-dependent propagation models are significantly influenced by the quality and resolution of atmospheric data used in system performance predictions.

Requirements imposed by modern weapons systems motivate the Naval Meteorology and Oceanography (METOC) community to constantly evaluate new technologies to improve upper atmospheric data products by improving spatial resolution and increasing the observation frequency and timeliness. Current upper-air observing systems utilized by ships at sea, such as the balloon-borne mini-rawin system (MRS), provide atmospheric data that may not have sufficient spatial and temporal resolution for propagation assessments supporting modern advanced-radar combatants. Also, since the balloon is advected by the atmospheric winds it may be frequently carried miles away from the ship in the middle and upper troposphere. Therefore, data obtained by balloon-borne sondes is not necessarily representative of the environment in the immediate

vicinity of the ship in the upper atmosphere.

Another concern is that the launch and data collection process consumes approximately 30 minutes to 2 hours per MRS sounding, and requires significant logistical support. These weaknesses in data acquisition ultimately impact the derived environmental products and tactical decision aids supporting warfare requirements. In order to achieve the goal of improving environmental products, the METOC community must strive for better resolution, timeliness and accuracy of the data that feed the derived products.

Refraction model accuracy can be optimized by use of fine-scale vertical profiles of temperature and water vapor density that are made within the region for which propagation loss is to be calculated. These are the two essential parameters for predicting atmospheric refractivity. These are the parameters measured by the LIDAR instrument, LIDAR Atmospheric Profiler System (LAPS). LIDAR technology, coupled with regional mesoscale atmospheric models, offers the capability to continuously and remotely describe atmospheric properties. Retrieval algorithms convert backscattered laser energy into a vertical sounding of the atmosphere in the ship's immediate vicinity. LIDAR technology has been examined for atmospheric measurements since the mid-1970's. Kunkel, K.E., et al., 1976, Painter, S.S., 1990, Philbrick, C.R., 1987 Sanh Lee, H., et al., 1996, and Senff, C., et al., 1994. The DOD and DOE have supported LIDAR research for atmospheric soundings since the early-1990's at the APL/PSU facility; Philbrick, C.R., 1994; Philbrick, C.R., et al., 1994; Stevens, T.D., et al., 1996; Haris, P.A.T., et al., 1995; Haris, P.A.T., 1996; Philbrick, C.R., et al., 1987; Philbrick, C.R., 1991; Rajan, S., et al.,

1994; Rajan, S., et al., 1995; and Balsinger, F., et al., 1996.

LAPS also provides distinct advantages over the traditional balloon-launched radiosonde. LAPS is capable of providing atmospheric profiling data regardless of wind conditions or sea state when balloon launches are difficult. Also, the setup/launch/data retrieval cycle of a balloon radiosonde typically consumes at least 30 minutes, whereas the LAPS can provide continuous soundings and real-time characterization of the local atmosphere.

This thesis will concentrate on the analysis and comparison of recent simultaneous LAPS LIDAR measurements and radiosonde profiles gathered during a recent operational demonstration and validation aboard the USNS SUMNER (T-AGS 61). Comparisons of refractivity profiles derived from MRS and LAPS sounding pairs are the primary means for correlating data. Other influencing factors, such as daytime versus nighttime measurement capability and shipboard interference, are assessed as well. This study will examine LIDAR's viability for the U.S. Navy's present and future atmospheric sounding needs.

II. BACKGROUND

Modern U.S. Navy combatants face technologically advanced threats which present the warfare commander the challenges of reduced reaction time, optimizing use of sophisticated sensor and weapon suites, and operations within varying environments. To be effective against threats such as high-speed, low-flying missiles, e.g. an air-launched Exocet, these systems and operational tactics require frequent and accurate assessment of the environment's impact on EM propagation prediction. Tactical decision aids have become increasingly common in supporting the warfare commander and enhance his ability to successfully employ EM sensors.

A description of the lower-atmospheric profile of temperature and humidity is the single most important environmental requirement for predicting the performance of a surface-based EM sensor, such as advanced shipborne surface-search radars. In the highly variable spatial and temporal littoral zone, it is increasingly important that data gathered for atmospheric modeling be fine-resolution, accurate, and real-time. The balloon-borne sonde (MRS) system currently in use is based on decades-old technology and may not meet the above requirements to satisfy performance assessment programs for modern and future sensors. It has relatively coarse temporal and spatial resolution and significant logistics requirements.

In an effort to meet this challenge, the Program Management of the Space and Naval Warfare Systems Command (SPAWAR PMW-185) and the Office of the Oceanographer of the Navy (OP-096) initiated and funded research and development for

a laser-based atmospheric profiling system.

Two Light Detection and Ranging (LIDAR)-based sounding instruments have been developed at the Applied Research Laboratory of Pennsylvania State University (ARL/PSU); the first system, the LIDAR Atmospheric Measurement System (LAMP) was completed in 1991. The LAMP system is housed in a large trailer and is physically cumbersome. Originally designed for sensing upper-atmospheric temperatures, it was deployed aboard the German research ship, RV Polarstern, and was used during the Latitudinal Distribution of Middle Atmospheric Structure (LADIMAS) experiment which took place between September 1991 and January 1992 [Philbrick et al., 1992]. Further experimentation tested the limits of the LAMP's temperature-sensing abilities in the lower atmosphere and lead to the implementation of rotational Raman technique [Rau, 1994; Harris, 1995]. This and other improvements derived from LAMP testing and data evaluation and were incorporated into the LIDAR Atmospheric Profiler System (LAPS), which was completed in April 1996.

Directed more toward U.S. Navy needs, the primary environmental data to be gathered by the LAPS are vertical measurements of temperature and water vapor density in the lower atmosphere. Detailed low-altitude sampling of these two variables is essential for assessing refractivity conditions. In order to fully optimize refractivity model accuracy for a particular shipboard sensor, these measurements should be made *in-situ*. The temperature profile and the surface pressure measurement provide the essential atmospheric density profile. LIDAR technology offers the capability to continuously and remotely sense these atmospheric properties. Retrieval algorithms convert rotational and

vibrational Raman backscattered laser energy into a vertical atmospheric sounding in the ship's immediate vicinity. Refractivity assessments and input for other METOC-oriented tactical decision aids could be available on-demand and the inferred knowledge to use and exploit the environment would be at the warfare commander's disposal. Detailed characteristics of the LAPS are discussed in Chapter V.

Other existing technologies can replace or augment the traditional radiosonde, including the Tactical Dropsonde (TDROP), and the Low Altitude Rocket Dropsonde System (LARDS). While both these systems have the advantage of providing high vertical resolution sounding data all the way to the sea surface, neither provides a continuous, on-demand data flow. In its present configuration, the LAPS cannot sense atmospheric properties below the height of its transmitter, however planned future improvements will allow for that capability.

III. ATMOSPHERIC PROPAGATION

A. INDEX OF REFRACTION

From an atmospheric sounding, the direction of travel of the EM wave front can be calculated as influenced by refraction. Variations in temperature, pressure and humidity cause changes in the atmosphere's density and result in refraction of EM waves. Refraction of an electromagnetic wave front causes its ray to change direction/bend as it passes through a medium. The degree of bending is determined by the gradients of the index- of- refraction, n, along the wave front. The index-of-refraction is related to the ratio of the velocity of propagation in free space, c, and the velocity of propagation within the medium, v; such that:

$$n = c/v \tag{1}$$

Free space propagation is a wave's velocity in a vacuum. In free space, the *ray path* or direction of propagation of an EM wave is a straight line and transmission is described as 'line of sight'. However, due to density changes in the atmosphere, the index of refraction generally increases with height. Thus, with the assumption of a normal atmosphere (i.e. horizontally homogeneous, standard atmosphere), radars would still have slightly extended over-the-horizon detection ranges as waves are bent toward the ground by the vertical gradient of n values.

Scattering theory can be used to predict the propagation path of an EM wave as it travels through a medium with varying densities or indices of refraction. Calculating the new direction of a wave's path as it propagates into a different density layer of the medium is possible provided the initial direction of travel is known. With today's advanced radars, including those with steerable beam emissions, the refractive effects become extremely important in describing low-elevation target locations.

B. REFRACTION IN THE TROPOSPHERE

The troposphere is the primary region through which shipboard and airborne radar EM energy propagates. For simplification of calculations, assume that the atmosphere is *isotropic*, or has the same properties in differing directions, and frequency dependency is removed from the index--of--refraction calculations. Normal values of n for the atmosphere near the earth′ s surface range between 1.00025 and 1.00040 (Patterson 1988). For convenience, an empirically derived scaled index of refraction, N, or refractivity, is defined as:

$$N = (n-1) \times 10^6 \qquad (2)$$

In the lower atmosphere, the error propagation relationship between refractivity gradient dN/dz and atmospheric variables pressure, P *(mbar)*; temperature, T *(^oK);* and specific humidity, q *(gm/kg)*; is given by:

$$dN/dz = 6.7\ dq/dz - 1.35\ dT/dz + 0.35\ dP/dz \tag{3}$$

Typical near-surface temperature gradients in a well-mixed, moist atmosphere are about -6.7 ° C/km, while at upper altitudes the dry troposphere is characterized by a temperature gradient of -9.8° C/km (dry adiabatic lapse rate). However, equation (3) shows that water vapor is the most significant atmospheric variable affecting refractivity. The water vapor content of the typical troposphere frequently exhibits strong gradients with height. At an altitude of 1500 m the water vapor content is normally about half of that at the surface.

The EM ray is normal to the actual EM wave front and is used to describe the direction of propagation. The propagation bending radius (r) of an EM ray is based on the gradient of n:

$$r = -1/(dn/dz) \tag{4}$$

As previously described, EM waves will bend downward from a straight line path as the index of refraction decreases with height. A trapping layer exists if the gradient of the index-of-refraction decreases enough to have the ray's curvature (radius) be the same as the earth's. It is convenient to have an descriptor for such conditions, which is called the modified refractivity, *M,* given by the expression:

$$M = N - 10^6\ x\ z/R_e \tag{5}$$

where height, z *(km)*, radius of the earth, R_e *(km)*, and refractivity, N, are considered. In a standard atmosphere, M typically increases with height. The gradient of M will not change with height, dM/dz = 0, in a trapping layer. Hence, dM/dz replaces dN/*dz* to provide a clear interpretation. The use of the modified refractivity index becomes advantageous in graphical displays for easy identification of trapping layers and ducts. Since -0.157N/m is the gradient associated with the ray curvature being equal to the earth's curvature and –0.040 N/m is the standard, the modified refractivity simplifies the identification of regions of trapping or ducting conditions. Table 3.1 summarizes various refractive conditions for vertical gradients of N and M.

	N - Gradient	M - Gradient
Sub-refractive	>0/m	>0.157
Normal/Standard	-0.079 to 0/m	0.079 to 0.157/m
Super-refractive	-0.157 to -0.079/m	0 to 0.079/m
Trapping	<-0.157/m	<0/m

Table 3.1 Conditions of Refractivity (after Patterson 1988).

C. ATMOSPHERIC TRAPPING LAYERS AND DUCTS

A trapping layer is a region in which the radius of a ray is less than the radius of the Earth's surface as the result of the refractivity gradient. A duct is associated with a trapping layer and is an atmospheric 'channel' in which electromagnetic energy can propagate to extended ranges. Ducting acts a barrier for energy crossing the duct boundaries, creating areas of reduced radiation coverage, called *radar 'holes'* or *shadow zones*, and present problems for systems operating above, below or in the duct.

Several well documented synoptic and mesoscale atmospheric conditions can lead to duct formation. It is not the purpose of this thesis to describe all ducting manifestations and their impact on EM emissions. One refractive condition that is prevalent over the ocean is a surface trapping layer associated with the humidity gradient immediately above the surface. This is referred to as the evaporation duct. It is worthwhile noting that an evaporative duct thickness is generally less than 30 m, and the world average is approximately 13 m (Patterson 1988). An approximate 15 m thickness causes the evaporation duct to be well below the first and lowest LAPS sounding height of 37m, which represents the first 75 m range bin. Evaporative ducts can also be embedded within a thicker surface-based duct.

A concern in describing atmospheric profiles is the vertical resolution required to describe significant atmospheric layers within capabilities of current operational propagation models, such as the Radio Physical Optics (RPO) EM assessment model. Dockery (1997) presented results from a study of thousands of helicopter soundings that

demonstrated the extreme variability of refractivity profiles in the lower troposphere, particularly below 1000 ft. Furthermore, surface evaporation and low-level temperature inversions can produce large irregularities below 300 ft. When considering surface-based systems, vertical location and strength of refractive features dictate that the vertical resolution of any given atmospheric measurement system be a relatively small fraction of sensor height. The 75 m resolution of the LAPS system used aboard USNS Sumner (T-AGS 61) does not fulfill this requirement. As a consequence of the study based on RPO, Dockery (1977) suggested vertical resolutions for both water vapor and temperature as 10 ft for altitudes between 10 to 500 ft, and 25 ft for altitudes between 500 and 2000 ft (Dockery, 1997). Resolutions less than these may not properly account for conditions that are important for detection of threats that are at low altitude and have low radar profiles.

IV. METHODS

A. BALLOON-BORNE SONDES : MINI-RAWIN SYSTEM

Atmospheric profiles at civilian and military airports, weather stations and onboard U.S. Navy ships underway are currently obtained with balloon-borne sondes. Several manufacturers exist and procedures for their use are well known. The type used by the Navy is the Vaisala MARWIN MW 12 Rawinsonde Set. The set is small and portable, and transmits measurement of upper-air vector wind, pressure, temperature, and relative humidity to the ground-based receiver set. Using balloon-lifted RS 80 Series radiosondes, the MRS fulfills Navy environmental data needs for *in-situ* refractive assessments onboard ships at sea. RS 80-15N Radiosonde physical characteristics are listed in Table 4.1; performance specifications are listed in Table 4.2. The accuracy of each sensor is noteworthy, since the MRS sounding data are being used as the baseline for comparison with the LAPS sounding data. The non-Global Positioning System (GPS) radiosondes were used in this experiment; GPS sondes are considerably more expensive (approximately $250/launch).

The need for continuous data measurements should also be considered. There is an operational disadvantage of the rawinsonde due to low time frequency and labor-intensive procedures required . One disadvantage is that the balloon-borne sonde cannot be considered an all-weather instrument capable of providing meteorological data regardless of sea-state or wind conditions. If the winds and seas are too high, they may

preclude a technician from working topside on a small combatant and would not allow for the launching of weather balloons. If winds alone are too high, it often becomes too difficult to get a balloon inflated and launched without bursting. In addition, maneuvering the ship, particularly small combatants, is frequently required to reduce the relative winds across the flight deck. A second disadvantage is the amount of time to make a launch. Balloon launching of a radiosonde requires 20 to 30 minutes for preparation, balloon filling, and release and it may take another 30 to 45 minutes to obtain the requisite data for low altitude profile analysis, and as much as two hours for a full profile.

B. LAPS LIDAR

The LAPS system development was an extention of the LAMP LIDAR research instrument; Philbrick, C.R., 1994; Philbrick, C.R., et al., 1994; Philbrick, C.R., 1991. It was developed because of identified requirements imposed by operational considerations for lower tropospheric soundings over the sea. The LAPS program began in 1991 with a 5-year goal of developing a prototype sounder instrument for demonstration and validation at sea. The necessary capabilities included *in-situ,* real-time measurement of atmospheric properties, primarily those that provide refractivity profiles needed for EM performance prediction products, namely water vapor and temperature. Measurements up to a minimum of 7 km were suggested by the EM/EO community, Space and Naval Warfare Systems Command (SPAWAR) Program Management (PMW-185), with a strong emphasis below 3 km. The unit developed at the APL/PSU has achieved these

goals and also interfaces with the Tactical Environmental Support System (TESS-3) interface as a possible Shipboard Meteorological and Oceanographic Observation System (SMOOS) sensor.

The LAPS LIDAR uses an Nd:YAG laser to create vibrational Raman scatter to measure water vapor density, and rotational Raman scatter to measure temperature. The ratio of vibrational Raman signal backscatter from water vapor molecules at 295 nm and 660 nm (second and fourth harmonics of the laser) to the signals from molecular nitrogen at 285 nm and 607 nm are detected by a sensitive receiver, filtered and processed for conversion into a water vapor density profile. The rotational Raman backscatter is similarly converted from the ratio of the signals at 528 nm and 530 nm wavelengths to measure atmospheric temperature. By using ratios for these measurements, the instrument provides robust data products without the need for any measurements of absolute sensitivity, gain or efficiency. Use of the ratio also removes or minimizes problems while measuring in the presence of interferences from aerosols and clouds.

During daylight periods, 'solar blind' wavelengths from 260 nm to 300 nm are used to minimize the effect of the sun's ultraviolet (UV) interference. Visible spectrum water vapor channels are not available for daytime use as solar radiation in these frequencies overwhelms the sensors. Although not important for the purposes of this report, it is worth noting that the instrument has additional capabilities to measure true atmospheric extinction and the ozone profile. The LAPS LIDAR characteristics are listed in Table 4.3. During the operational demonstration, the LAPS LIDAR/receiver unit was mounted on the fantail of SUMNER, immediately aft of the superstructure and near the

port side. This arrangement became a factor in UV channels water vapor data accuracy due to contamination by diesel exhaust from the upper level discharge vents, as discussed in Chapter V. Figures 4.1 and 4.2 illustrate LAPS physical position on USNS SUMNER's deck. The performance of LAPS in high wind and sea states with spray is unknown.

C. DATA COLLECTION PROCEDURES

The experiment was conducted aboard USNS SUMNER (T-AGS 61) from 01 September to 15 October 1996. The ship departed from Pascagoula, MS and gathered data in the Gulf of Mexico while moving southward around the Florida peninsula. The crew enjoyed a one week hiatus from 21-28 September at Port Everglades, FL for the Oceans '96 Expo where CNMOC staff personnel and other participants were able to observe the LAPS in operation. The remainder of the cruise was conducted off the eastern Florida coast. A total of 97 MRS launches were attempted with 94 considered successful. Of these 94 soundings, 45 were conducted at night, 29 during daylight hours and the remaining 20 during transition periods of dawn or dusk. Nine additional soundings comparisons have been rejected for missing or incomplete data from either system.

Each MRS launch was coordinated for a concurrent LAPS sounding set. Since a typical MRS balloon ascent to 3 km lasts about 30 minutes, LAPS data has been integrated over a 30 minute range to match the approximate duration of the balloon flight.

Size	55 x 147 x 90 mm
Weight	Less than 200 g
Sampling Rate	1.5 sec (all parameters)
Solid State Construction Design	High technology BAROCAP, THERMOCAP and HUMICAP sensors
Cost per launch/sounding	approx. $150 (includes balloon, helium, radiosonde) (non-GPS)

Table 4.1 RS 80-15N Radiosonde Characteristics

PRESSURE SENSOR Type: Pressure Range: Accuracy: Resolution:	 Capacitive aneroid 1060 to 3 hPa 0.5 hPa 0.1 hPa
TEMPERATURE SENSOR Type: Temperature Range: Accuracy:Resolution: Lag:	 Capacitive bead -90° C to 60° C 0.2° C 0.1° C < 2.5 seconds
HUMIDITY SENSOR Type: Humidity Range: Accuracy: Resolution: Lag:	 Thin film capacitor 0 to 100% 2% RH 1.0% RH 1.0 second

Table 4.2 RS 80-15N Radiosonde Sensor Performance Specifications

Transmitter	Continuum 9030 - 30 Hz 5X Beam Expander	600 mj @ 532 nm 130 mj @ 266 nm
Receiver	61 cm Diameter Telescope	Fiber Optic Transfer
Detector	Seven PMT channels Photon Counting	528 and 530 nm - Temperature 660 and 607 nm - Water Vapor 294 and 285 nm - Daytime Water Vapor 276 and 285 nm - Raman/DIAL Ozone
Data System	DSP 100 MHz	75 m range bins (future upgrade to 7 m)
Safety Radar	Marine R-70 X-band	protects 6° cone angle around beam

Table 4.3 LAPS Characteristics

V. RESULTS OF PROFILE COMPARISONS

A. DATA COMPARISON

This thesis compares the results from simultaneously gathered atmospheric soundings by LAPS and rawinsondes (MRS) aboard USNS SUMNER (T-AGS 61). The Naval Postgraduate School (NPS) was responsible for the rawinsonde data collection and ARL/PSU for the LAPS LIDAR collection. The author was solely responsible for coordinating efforts of embarked U.S. Navy personnel who were conducting MRS launches, and preliminary data collection and processing. LAPS data collection and processing was the responsibility of APL/PSU scientists. Both teams worked together coordinating data collection periods. Navy personnel were given basic training and indoctrination to the operation of the LAPS systems. NPS personnel performed editing and processing tasks for the rawinsonde profiles. APL/PSU personnel performed editing and processing tasks for the LIDAR. Collaborative interpretations were made on the final joint LAPS LIDAR/MRS data sets.

This report will focus, when possible, on the modified refractivity, M, profile comparisons. This is only possible during the nighttime periods when temperature as well as water vapor values are retrievable from the LAPS. Temperature measurements are not available during daylight hours due to solar radiation interference. For M profile comparisons, data from both the LAPS and rawinsonde are displayed in 6-panel charts, to include profiles of temperature, specific humidity, and M, and the rawinsonde-LIDAR

differences.

Water vapor comparisons will be made during daytime as well as nighttime periods. This is an important separate comparison because water vapor retrieval is affected by daytime radiation contamination.

Post-cruise analysis of the profile data revealed four notable deficiencies in the LAPS sounding data compared to baseline rawinsonde data. The deficiencies, ranked from most problematic to least, are as follows:

1. Too coarse, 75 m, vertical resolution.
2. Upper altitude limitations of UV frequency (daytime) water vapor data.
3. Temperature data 'vignetting' below 1 km.
4. Diesel exhaust caused SO_2 contamination of UV water vapor profiles.

Other differences occurred, but the four listed above were considered the most serious because of the way they affected refractivity computations below 2000 m. In the following sections each deficiency will be examined separately, along with possible corrective measures. Deficiencies will be examined using modified refractivity (M), specific humidity, and temperature profiles. In some situations, a combination of these negative factors could have magnified errors with regard to refractivity descriptions. Whenever possible, discussions of the deficiencies will present the deficiency first, followed with a description of the cause. Remedies for all described shortfalls are under continuous study and formulation by scientists at the APL/PSU.

Seventy-seven Lidar/rawinsonde pairs were used in the analysis. To compare the rawinsonde and LIDAR differences between the 77 pairs, all rawinsonde and LAPS data

were interpolated to the same vertical grid. The first vertical level is at 50 meters and higher levels are at 75-meter intervals to 2000 meters. These levels were chosen because they were close to the heights of data points, and matched the 75-meter LAPS resolution. This process degrades the MRS data that has a vertical resolution of about 25 to 35 m.

The 77 profiles were distributed as follows; 48 Night, 18 Day, and 11 day/night Transition. Only 34 of the 48 nighttime LIDAR profiles have temperature data. The remaining 14 night profiles did not have reliable temperature data, but the specific humidity data is reliable and is used in the statistical analysis. The 18 Day, and 11 Transition profiles have only specific humidity data. Visible frequency daytime temperature measurement capabilities were not possible in the subject LAPS unit.

The Root Mean Squared (RMS) errors for temperature and specific humidity are listed in Table 5.1. Profiles of these RMS errors are shown in Figures 5.1 and 5.2. The RMS difference between the rawinsonde and LIDAR was calculated at each vertical level using all LIDAR/rawinsonde pairs or day, night, and transition subsets. This provides an estimate of accuracy at each vertical level for temperature, specific humidity and modified refractivity, M.

Figure 5.1 depicts the RMS differences for specific humidity calculated at each 75m vertical level for all 77 pairs, 48 night pairs, 18 daylight pairs, and 11 pairs during sunrise or sunset transition periods. Figure 5.2 depicts the RMS differences for temperature and modified refractive index, M, calculated at each 75-meter vertical level for the 34 night pairs with temperature data.

	Average rms. Difference between RAWINSONDE and LAPS *temperature* (^{0}C), 0-2000 m	Average rms. difference between RAWINSONDE and LAPS *water vapor*, (g/kg), 0-2000 m	Average rms. difference between RAWINSONDE and LAPS Modified Refractivity, 0-2000 m
Nighttime data	2.14	0.94	6.86
Transition (dawn/dusk)	N/A	1.58	N/A
Daytime data	N/A	2.41	N/A

Table 5.1 Temperature, Water Vapor and Modified Refractivity Statistics

1. Deficiency: Too Coarse, 75 meter, vertical resolution

A selected set of paired LIDAR/rawinsonde soundings were used to demonstrate resolution deficiencies that occur with the deployed version of the LAPS LIDAR. As described below, this limitation occurs because of the present commercial acquisition components rather than processing technology or physical understanding of LIDAR retrieval.

Figures 5.3 and 5.4 show conditions detected by the rawinsonde that were not adequately represented by the concurrent LAPS sounding. Figure 5.3 is a nighttime sounding pair showing both water vapor and M, while Figure 5.4 is a daytime sounding

pair showing only water vapor. In both cases, the coarse range resolution of the LAPS failed to adequately resolve sharp vertical changes in water vapor density. In Figure 5.3, a duct exists from about 300 to 570 m. Panel 2 in Figure 5.3 shows an extreme decrease in water vapor density at 570 m measured by the rawinsonde. However, the LAPS vertical resolution smoothes the curve and consequently does not accurately reflect the strength of the duct.

Figure 5.4 shows similar degraded water vapor resolution results during daytime soundings. Figures 5.5 and 5.6 are additional sounding pairs where rawinsonde discerned ducting by the LAPS did not. Comparisons of day and night water vapor further show that the vertical resolution of the LAPS LIDAR is obviously not affected by daylight conditions. However it must be noted that diurnal transients such as the evaporation duct do exist, so finer resolution is required for both day and night.

Figures 5.7 and 5.8 show night sounding pairs in which maximum M-value differences between rawinsonde and LAPS were as low as 1.5% for nighttime. When no significant atmospheric gradients exists, especially for water vapor, the LAPS and rawinsonde soundings compare very favorably, as would be expected. Figures 5.9, 5.10 and 5.11 show additional sounding pairs in which smooth water vapor profiles resulted in a close match between the M profiles of rawinsonde and LAPS. Under certain conditions, the water vapor profile had several gradient shifts; as long as the changes were not sharp or severe, LAPS accurately detected the difference. Figure 5.12 shows an example of very good tracking M profile by LAPS as the water vapor gradient shifted several times from positive to negative and vice versa.

Some conclusions are possible relative to the reason and impact of the deficiency. The reason for the deficiency in this deployment is the current technological stage of the LIDAR hardware development. The electronics hardware component that controls the LAPS receiver's data ingestion rate functions at a frequency of 100 GHz and the speed of the electronics limits the bin width to 500 nsec. This relatively slow cycle speed restricts vertical resolution to 75 m bins or range gates. In cases where sharp water vapor gradients were detected by the rawinsonde sensors, the LAPS failed to accurately describe the gradient in the moisture stratification. The impact of the resultant difference is that the LAPS M profiles do not portray ducting conditions as strongly and would have adversely affected the refractivity assessments and performance predictions.

Electronics technology is advancing rapidly and new, faster electronics packages available today can increase the LAPS receiver processing rate by tenfold. With the receiver operating at a 1 GHz frequency, the vertical range resolution can be refined to increments in the 3 to 7 m scales. This possible improvement might allow LAPS to surpass the ability of the rawinsonde to detect abrupt changes in water vapor and/or temperature profiles. Vertical soundings of atmospheric properties would then have requisite resolution to discriminate even small variations, and associated refractivity conditions could be described in detail. A single channel set of electronics which is capable of these advances has been tested a PSU during the past year.

2. Deficiency: Degradation of LAPS UV Water Vapor Channel

Another concern is the accuracy/stability of the LAPS data. Table 5.1 outlines

statistical differences between nighttime, transition and daytime sounding pairs. Profiles of RMS differences from which these values were derived are shown in Figure 5.1. The RMS profile for temperature and M are shown in Figure 5.2. The errors are larger than uncertainties in rawinsonde measurements and a particular concern is the increase during daylight hours. Since this thesis focuses on the atmosphere below 2000 m, the full effect of this problem cannot be demonstrated as clearly as the coarse vertical resolution deficiency, yet it is the most significant developmental challenge facing the LAPS program.

During daylight hours, solar UV radiation contaminates returning backscatter signal to the LAPS receiver except for the solar-blind ultraviolet wavelengths. During nighttime operation, both UV and visible spectrum frequencies can be exploited, however the visible spectrum data are generally superior. Statistical variations and errors, as compared to concurrent rawinsonde data, are minimized at night.

A means of evaluating the LAPS water vapor and temperature data 'stability' is through analysis of variations in the calibration coefficients required to correlate LAPS data to rawinsonde data. Figures 5.13 and 5.14 show visible and ultraviolet water vapor calibration coefficient plots versus chronologically numbered rawinsonde soundings. A constant calibration figure (straight line) would imply perfect correlation between the two systems; greater deviations reflect ambiguities and system errors. The average value for the water vapor calibration factor over the whole experiment for the visible channels was 133.2 +/- 6.2 (4.6%). This figure reflects removal of 7 cases where operator-induced problems caused erroneous readings due to prior overload on the visible channel detectors

in the daytime. Calibration of LAPS optical system requires approximately 10 minutes for stabilization. In these 7 cases, calibration lamps that were accidentally left activated overloaded the receiver's optics system. The instrument requires several hours to recuperate from an overload on the visible detectors caused by exposure to solar illumination or leaving the calibration lamp on. The average value for the UV channels was 22.4 +/- 2.0 (8.9%). This figure reflects removal of 5 cases where SO_2 contamination is suspected. This error source will be discussed in section 4 of this chapter. These calibration coefficient variations again highlight the significant difference between visible spectrum channels (nighttime) and UV spectrum channels (daytime). In the statistical evaluation of the calibration coefficients, daytime (UV channels) data is 2 to 2.5 times more erratic than nighttime (visible channels) data.

Corrective methods for improving the daytime LAPS water vapor data include removal of neutral density filters, which would allow greater dynamic range before saturation of Photo-Multiplier Tubes (PMT) and consequent improved data count. Also, new compact diode-pumped laser systems can improve the signal-to-noise ratio of returning backscattered data, which would reduce the effect of solar interference.

3. Deficiency: Temperature Data Vignetting

In nearly all cases with good data, a trend persisted in which initial LAPS temperature data became higher than rawinsonde data below approximately 1 km. Figure 5.2 clearly reveals an increase in temperature RMS below 100 meters for corrected

profiles. While it is not within the scope of this report to investigate laser optics physics, clearly the temperature data statistics from Table 5.1 are adversely affected by this error, even though corrections have been made. Simply, the error is a manifestation of the physics of the receiver's optics; as low-altitude backscattered rotational Raman data arrives at the receiver, the values are distorted by the vignetting. The error function for the vignetting has been determined from the ratio of the temperature data channels when a 530 nm filter is placed in each channel. Correction has been derived at the APL/PSU and it has been found to correct the low-altitude temperature data values to within approximately +/- .5 ^{0}C of rawinsonde temperature data.

Further advancements in processing Raman rotational backscattered signals may minimize or eliminate the 'vignetting' effect, however present correction functions may adequately compensate for the error.

4. Deficiency: SO_2 Contamination of UV Water Vapor Data

During one observation period, relative wind shifts as USNS SUMNER maneuvered from a relative headwind heading to a crosswind heading resulted in approximately 30% decrease of temperature calibration values over the course change. Similar errors in other profiles are of concern because of the ambiguous impact on profile structures.

This effect is caused by contamination by absorbing gases, e.g. SO_2, rather than by other radiation. The LAPS transmitter/receiver unit was located on the fantail of the

SUMNER where, in relative headwind conditions, exhaust from the diesel engines could be blown over unit. The SO_2 absorption band lies within the UV water vapor channels and its occasional presence resulted in anonymously high calibration coefficients in that spectrum for those periods. Full analyses of the effects of SO_2 contamination are ongoing at the ARL/PSU.

Depending on platform propulsion and auxiliary power systems, positioning of the LAPS sensor is critical to minimize SO_2 interference. During the operational demonstration aboard USNS SUMNER, shipboard mounting locations were limited and the problem was unavoidable. Obviously, permanent installations would require well-thought positioning to avoid this effect.

VI. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

The LAPS operational demonstration aboard USNS SUMNER is considered highly successfully based on system reliability and proof of concept. The LAPS was available for the entire duration of the experiment and, except for a brief planned maintenance period, suffered no 'down time'. More important however is the fact that the system was able to successfully gather real-time environmental *in-situ* data in an operational setting aboard a ship at sea.

Shortfalls discovered in this study are: relatively coarse vertical resolution, degraded daytime data due to scattering, sometimes erratic temperature measurements, and ship's gas absorption. Of the four significant discrepancies, improvement to daytime UV channels water vapor data as well as availability of daytime temperature data remain as a serious challenges for LAPS LIDAR engineers. New laser technology, such as compact diode-pumped power supplies, should contribute positively toward solutions.

B. RECOMMENDATIONS

LAPS has demonstrated some potential for gathering information aboard U.S. Navy combatants and land stations for sounding the lower atmosphere. Present and future advanced combat systems require continual updates on the refractivity environment in

order to optimize performance and response. LIDAR is a candidate technology for providing such a data stream and continued investment in its development. It is critical that future LAPS measurements provide daytime temperature profiles and higher vertical resolution. Additional at sea testing is then required to evaluate these improvements.

C. ADVANCED LAPS (ALAPS)

The concept for the next generation of LAPS includes other improvements which will render the system even more appealing to the warfighter customer. With an eye-safe UV laser frequency and steerable LIDAR beam, sampling of the atmosphere from the surface and through the surrounding volume will be possible. Vertical resolution in the near-surface layer will be as fine as 20 cm as LIDAR beams can be directed at shallow angles to the sea surface. The resultant highly-detailed characterization of the evaporation duct would greatly enhance a ship's combat systems to exploit this feature.

Additionally, automated ALAPS operation through self-calibration would yield a virtually 'hands-off' system, and straightforward data displays, such as false-color refractivity profiles, would also contribute to the user-friendliness of the system. Wind velocity measurement and electro-optical environment sampling would also be available. The growing requirement for an atmospheric sounding system that is in keeping with the pace of advancing combat system technology is clear, and LIDAR is a promising technology.

Figure 4.1 Side View of LAPS unit on USNS Sumner (T-AGS 61) Fantail

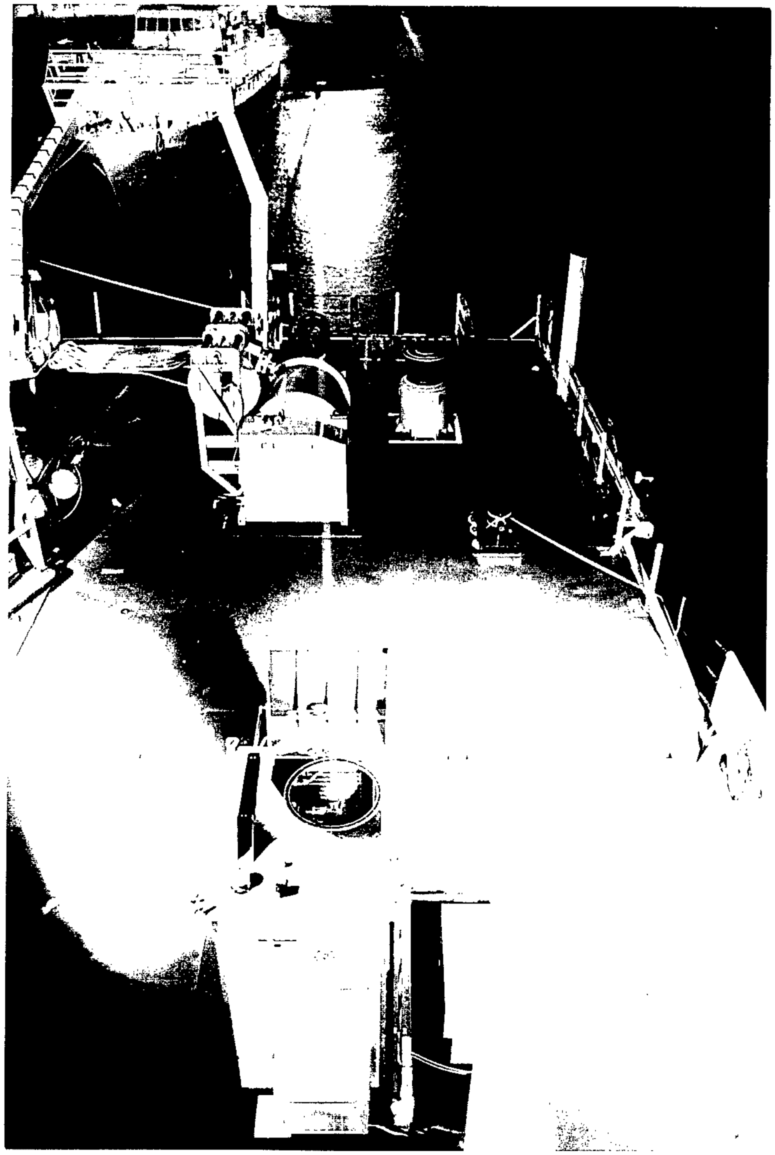

Figure 4.2 Overhead View of LAPS unit on Sumner (T-AGS 61) Fantail

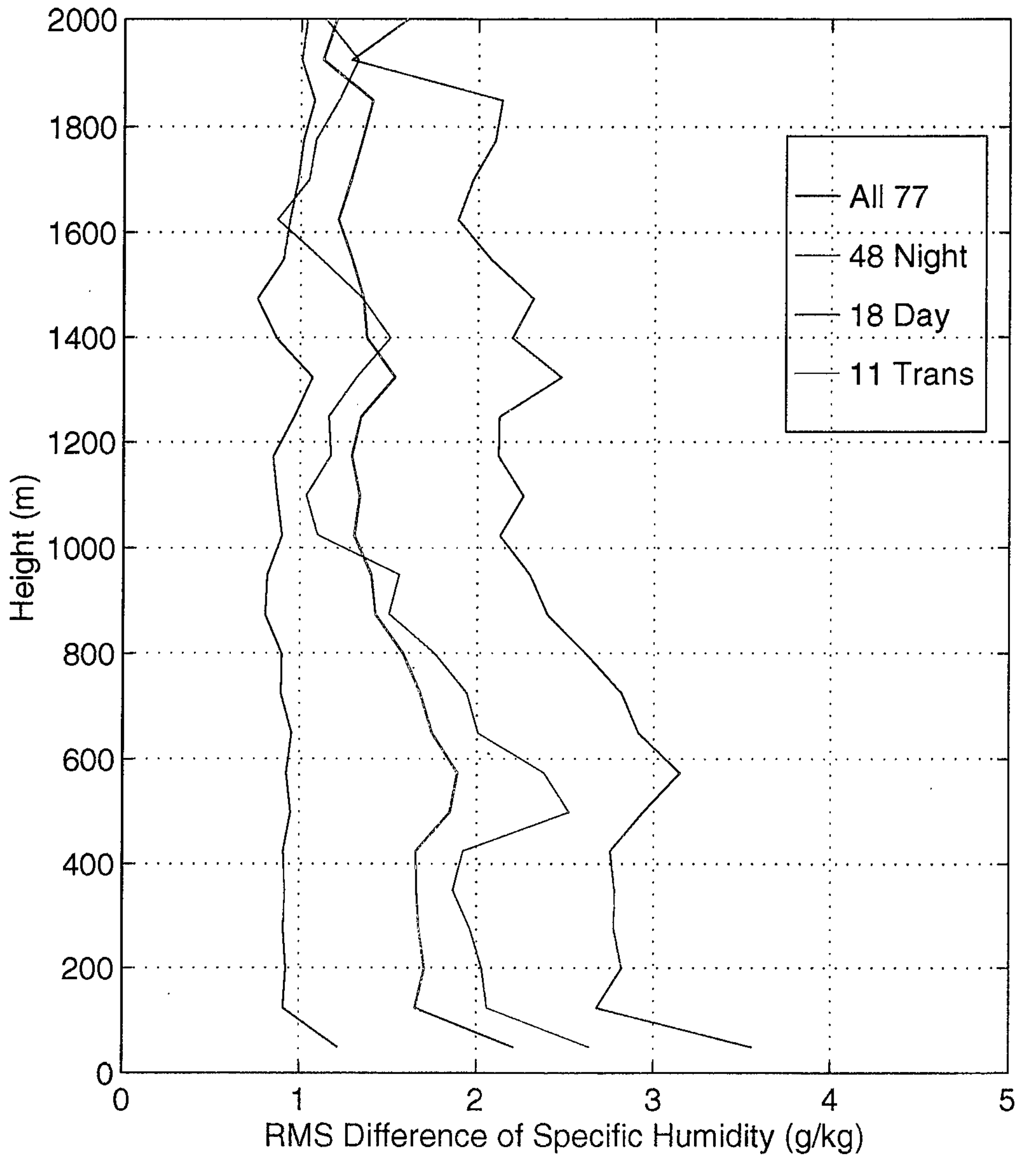

Figure 5.1 RMS Difference of Specific Humidity (g/kg) to 2000 m

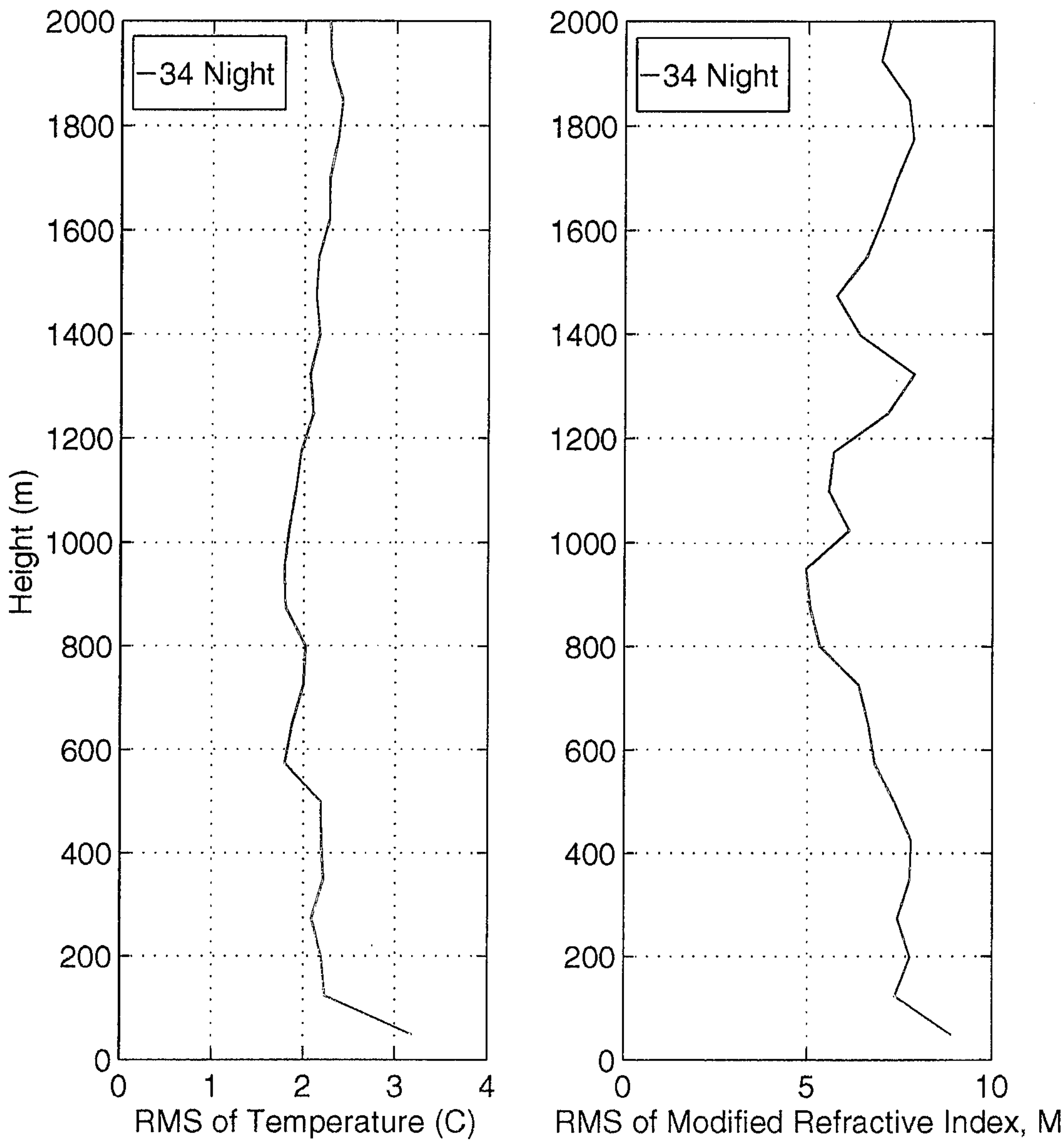

Figure 5.2 Left, RMS of Temperature (C) to 2000 m;
Right, RMS of Modified Refractive Indez, (M) to 2000 m

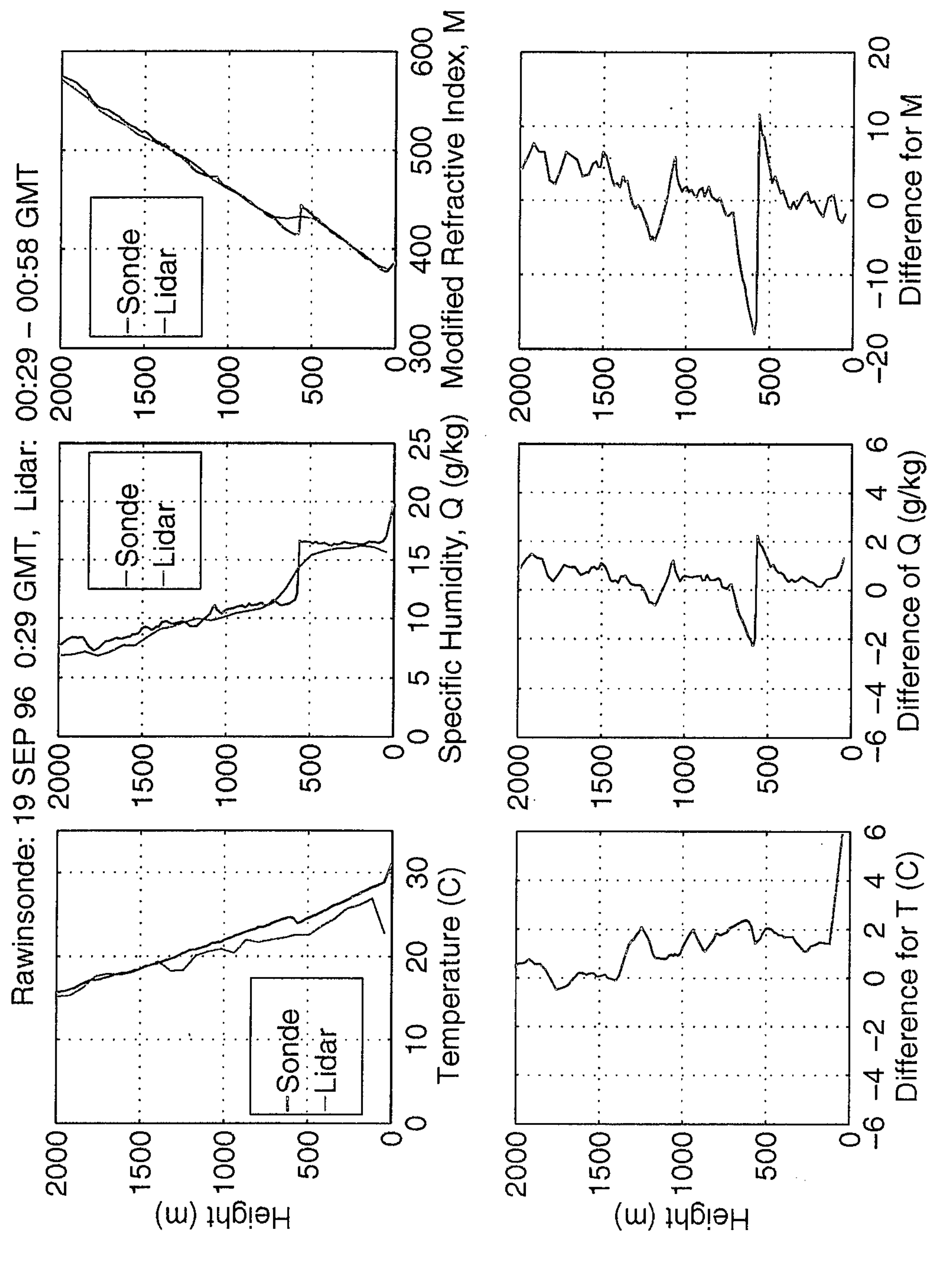

Figure 5.3 Comparison of 19 Sep 96 MRS and LIDAR data to 2000 m: Upper Left, Temperature (C); Lower Left, Temperature Differences; Upper Middle, SpecificHumidity, Q (g/kg); Lower Middle, Q Differences; Upper Right, Modified Refractive Index, M; Lower Right, M Differences;

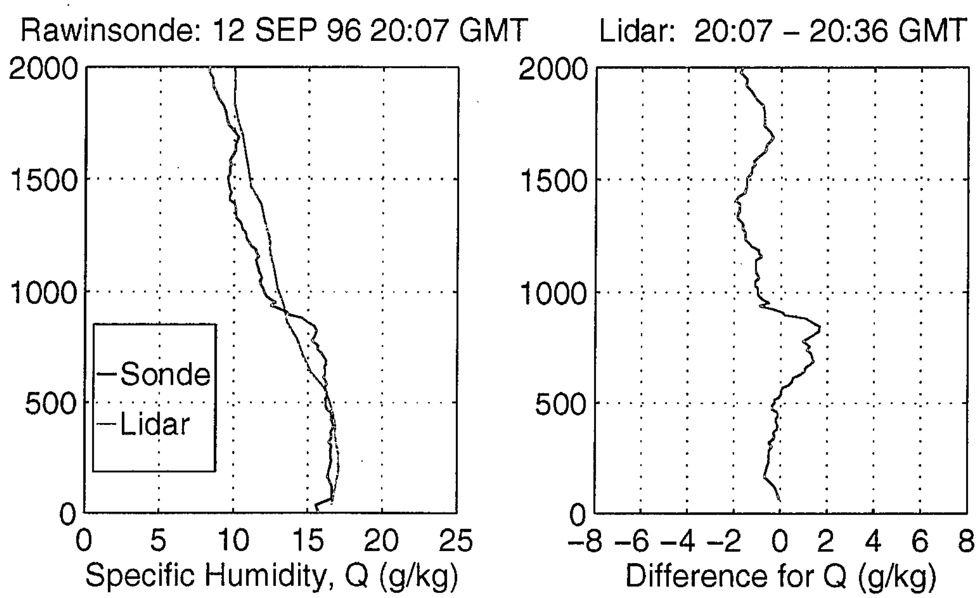

Figure 5.4 Comparison of 12 Sep 96 MRS and LIDAR data to 2000 m:
Left, SpecificHumidity, Q (g/kg); Right, Q Differences

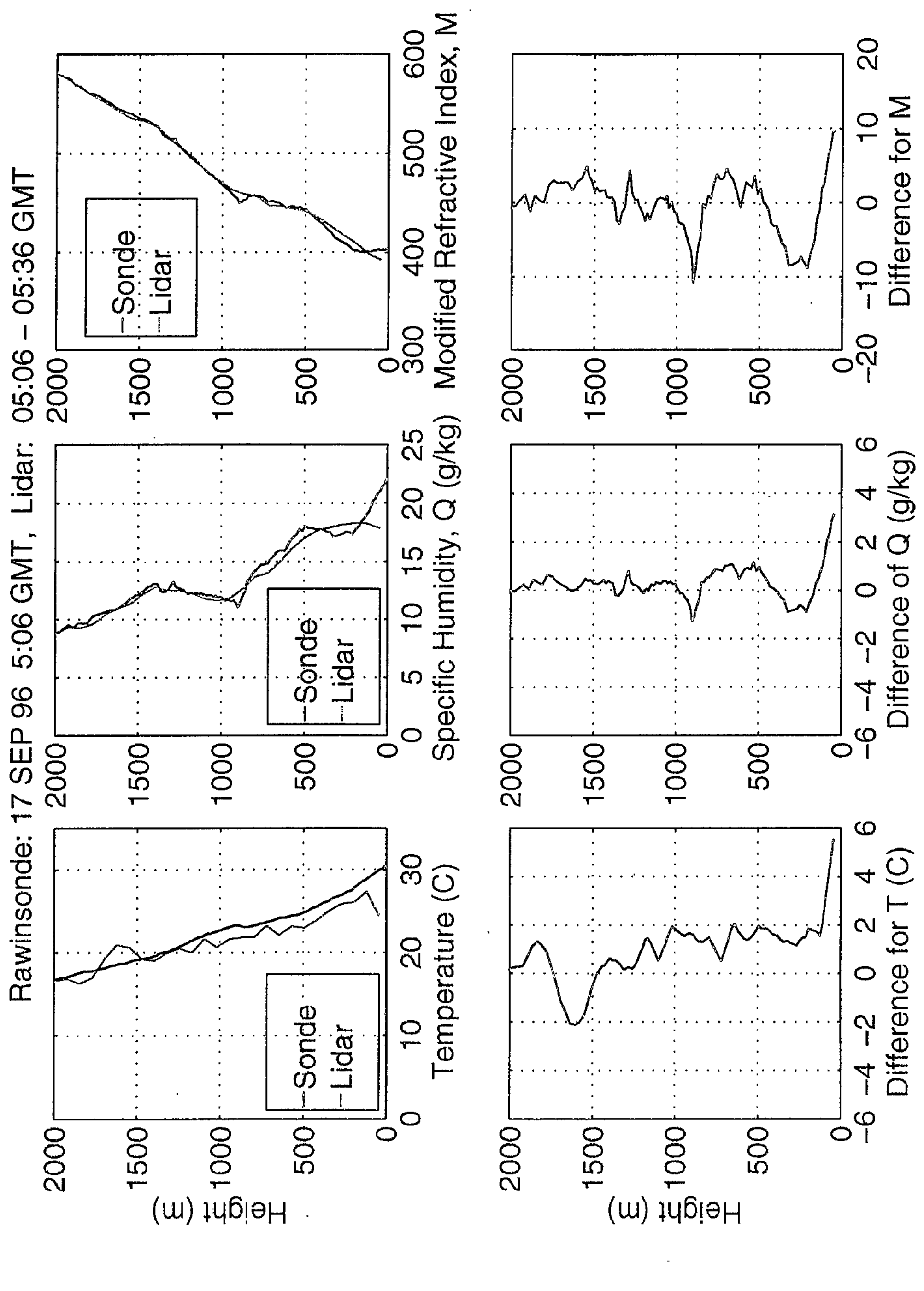

Figure 5.5 Same as Figure 5.3 for 17 Sep 96 data

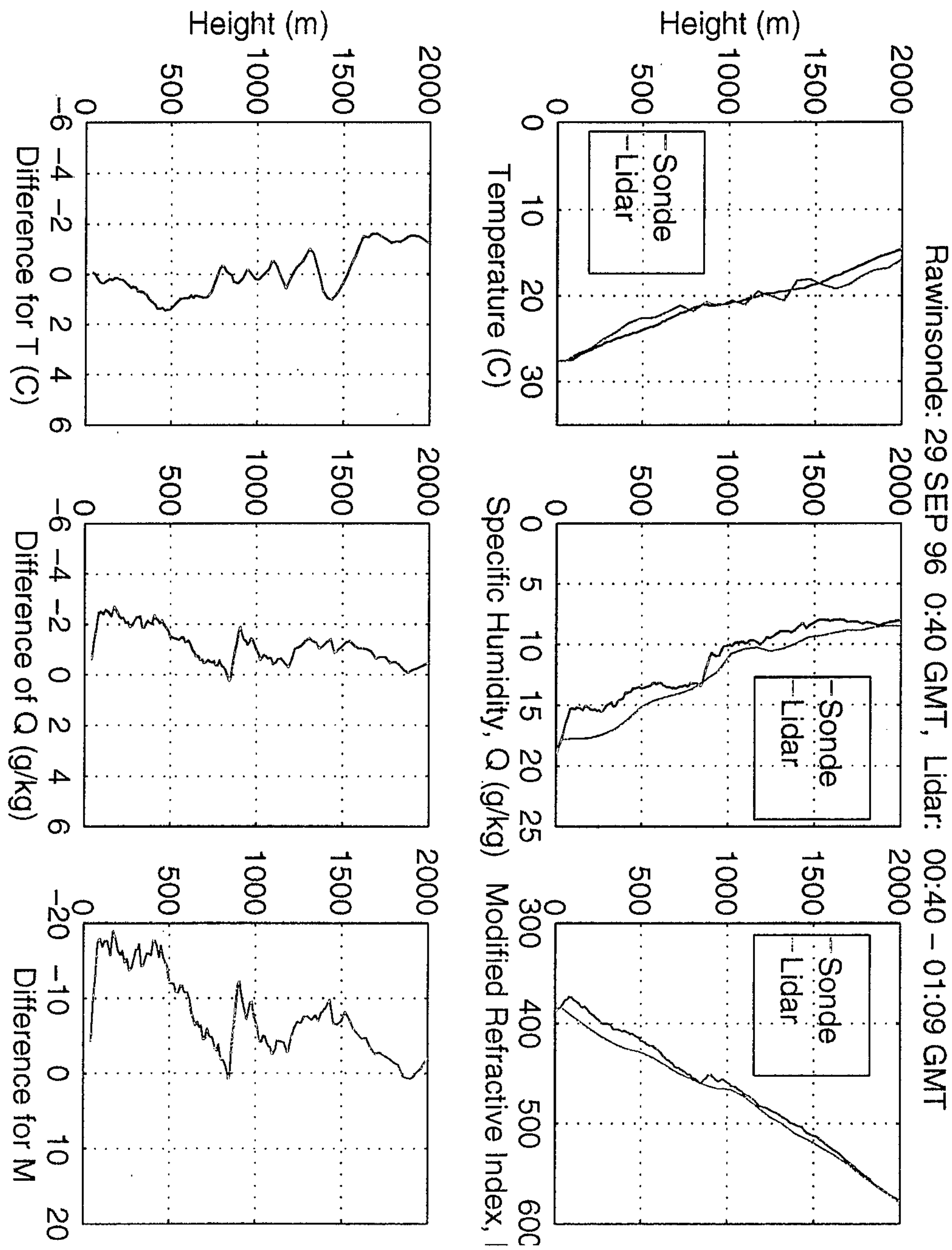

Figure 5.6 Same as Figure 5.3 for 29 Sep 96 data

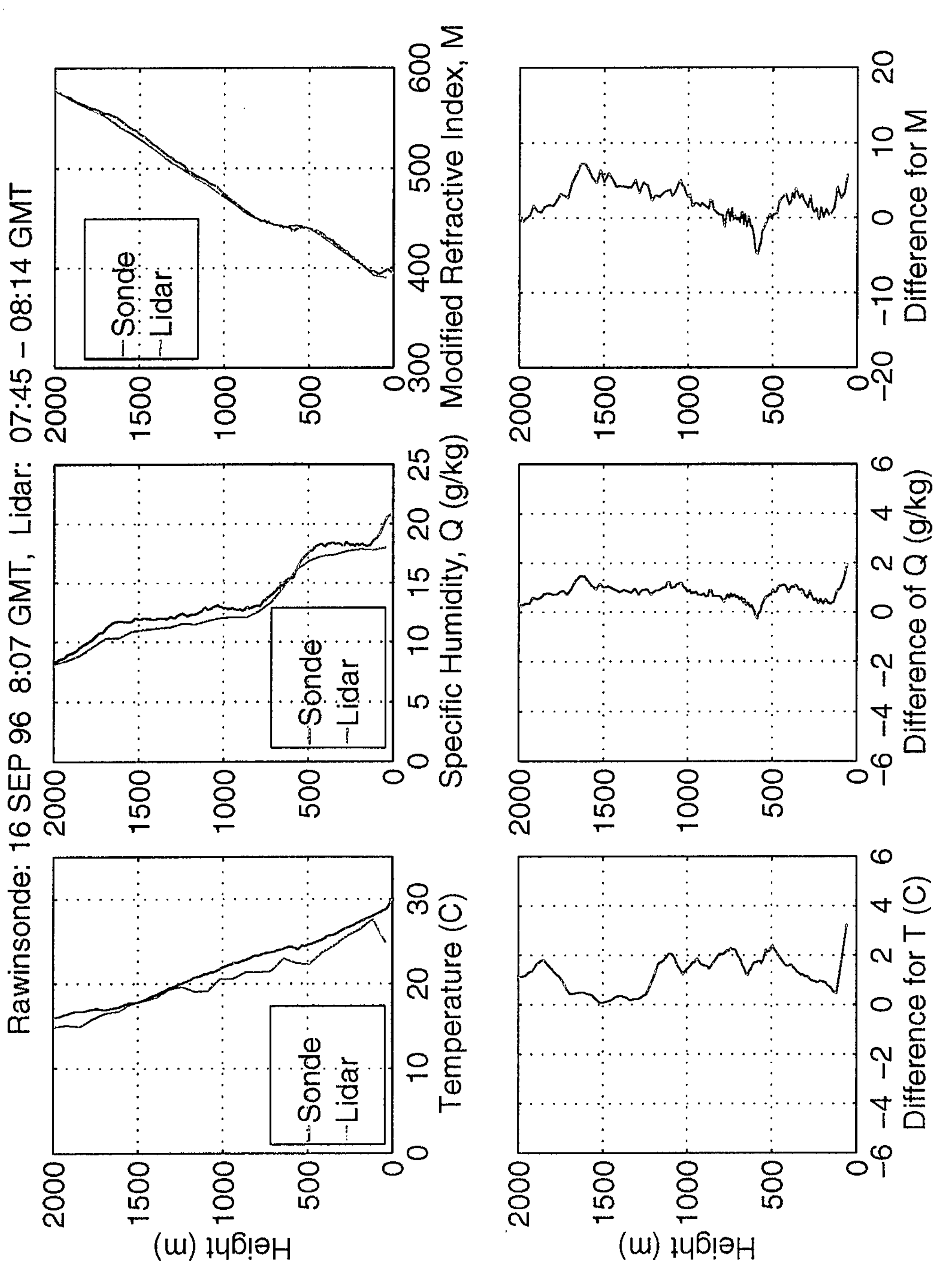

Figure 5.7 Same as Figure 5.3 for 16 Sep 96 data

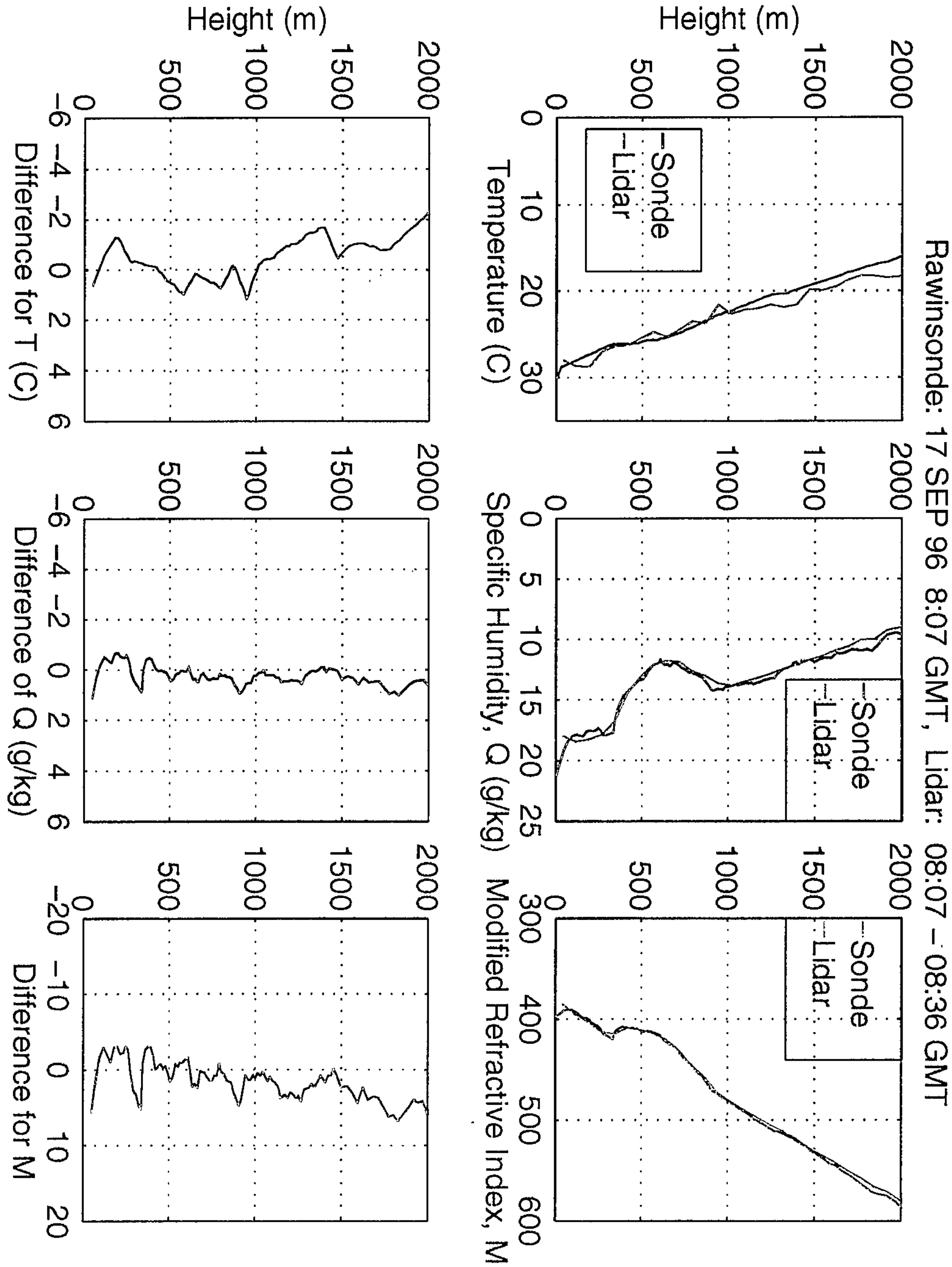

Figure 5.8 Same as Figure 5.3 for 17 Sep 96 data

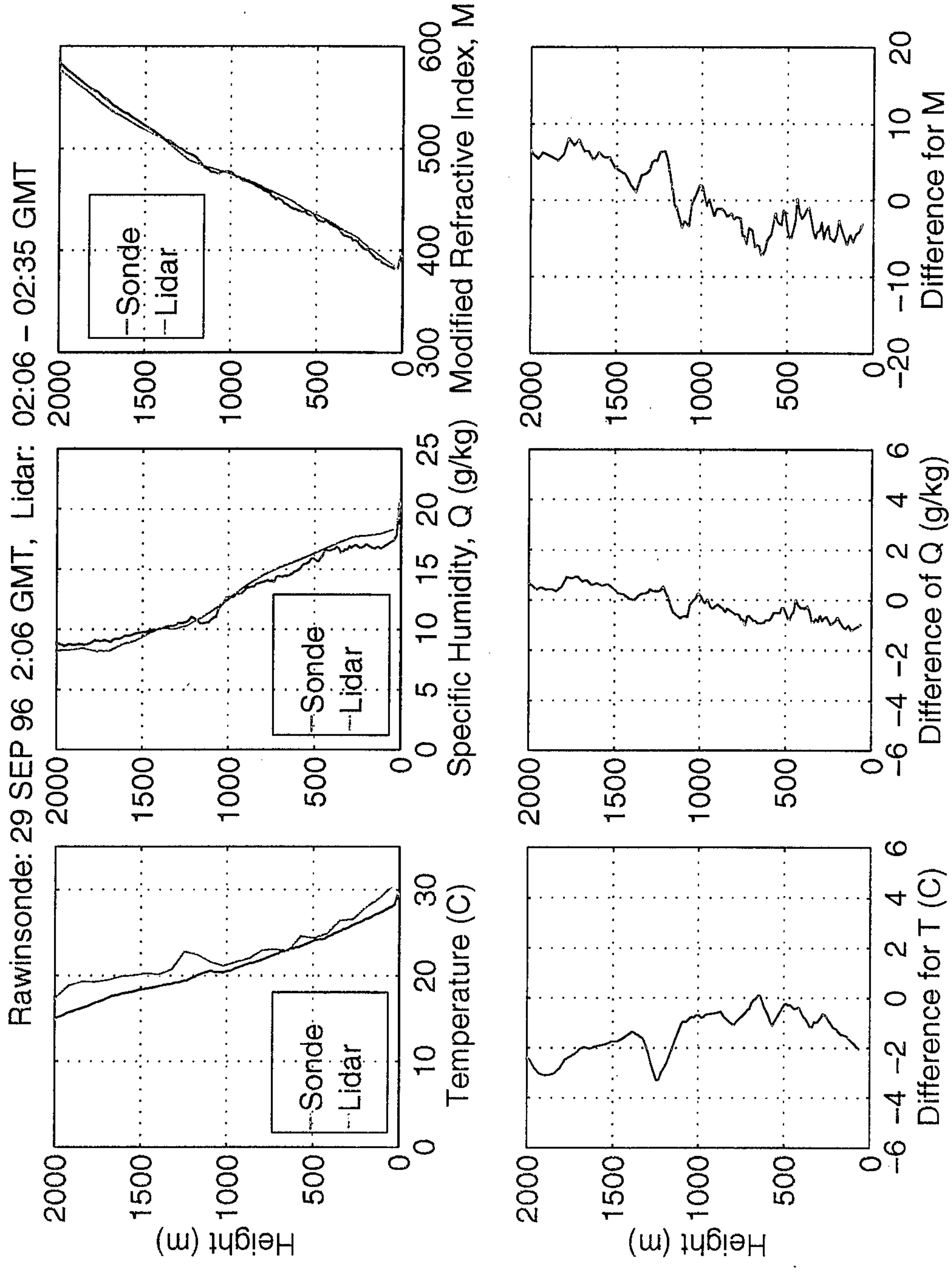

Figure 5.9 Same as Figure 5.3 for 29 Sep 96 data

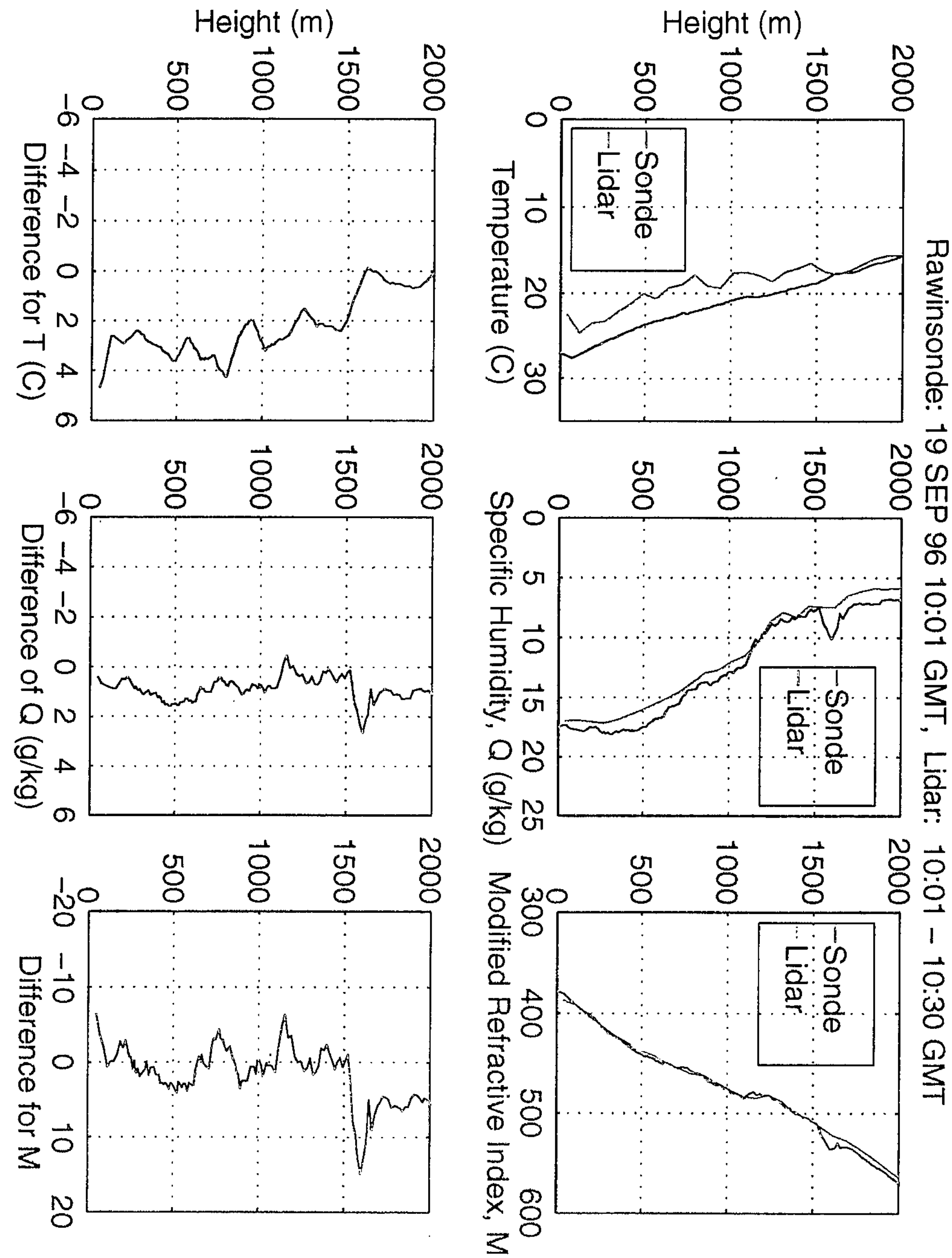

Figure 5.10 Same as Figure 5.3 for 19 Sep 96 data

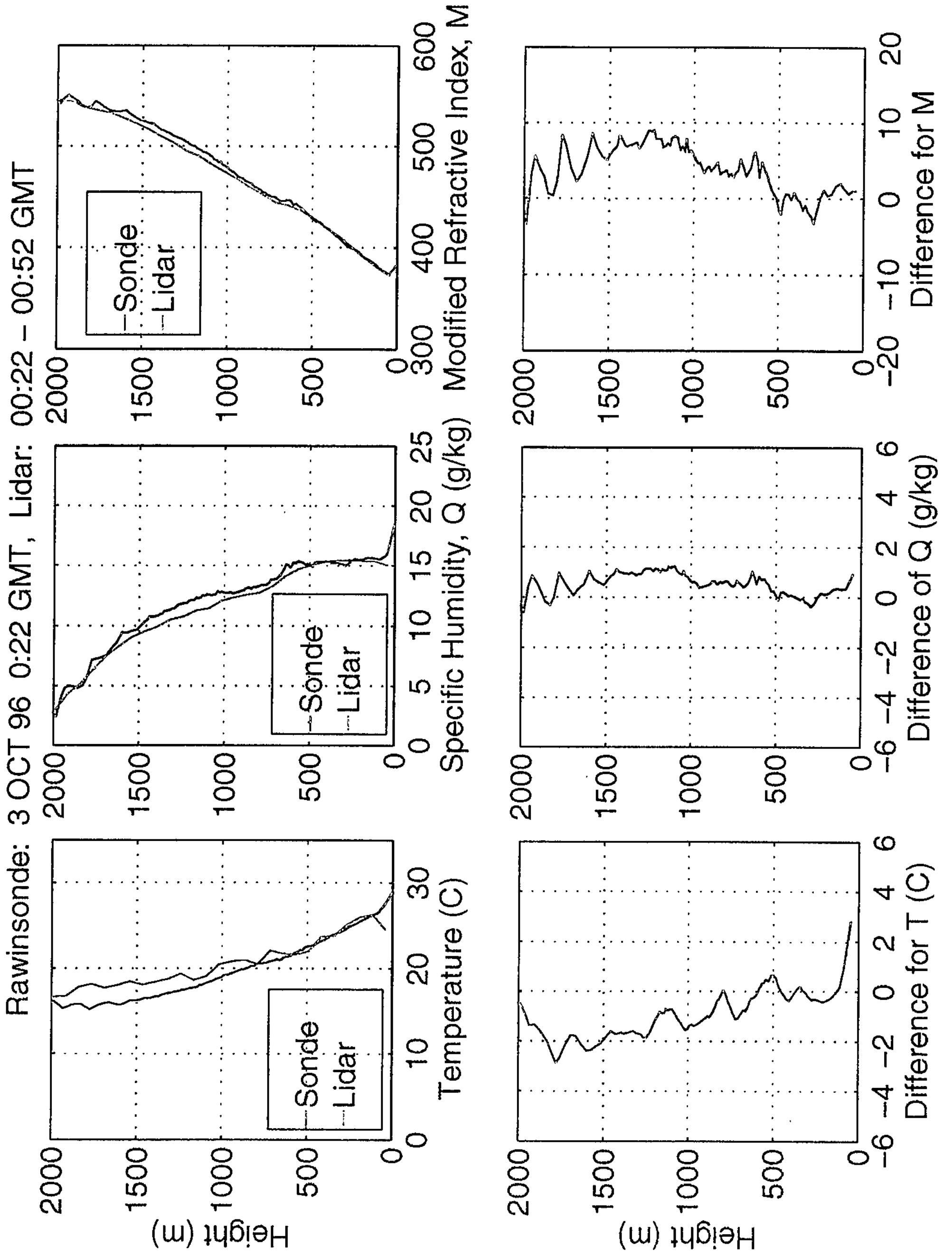

Figure 5.11 Same as Figure 5.3 for 03 Oct 96 data

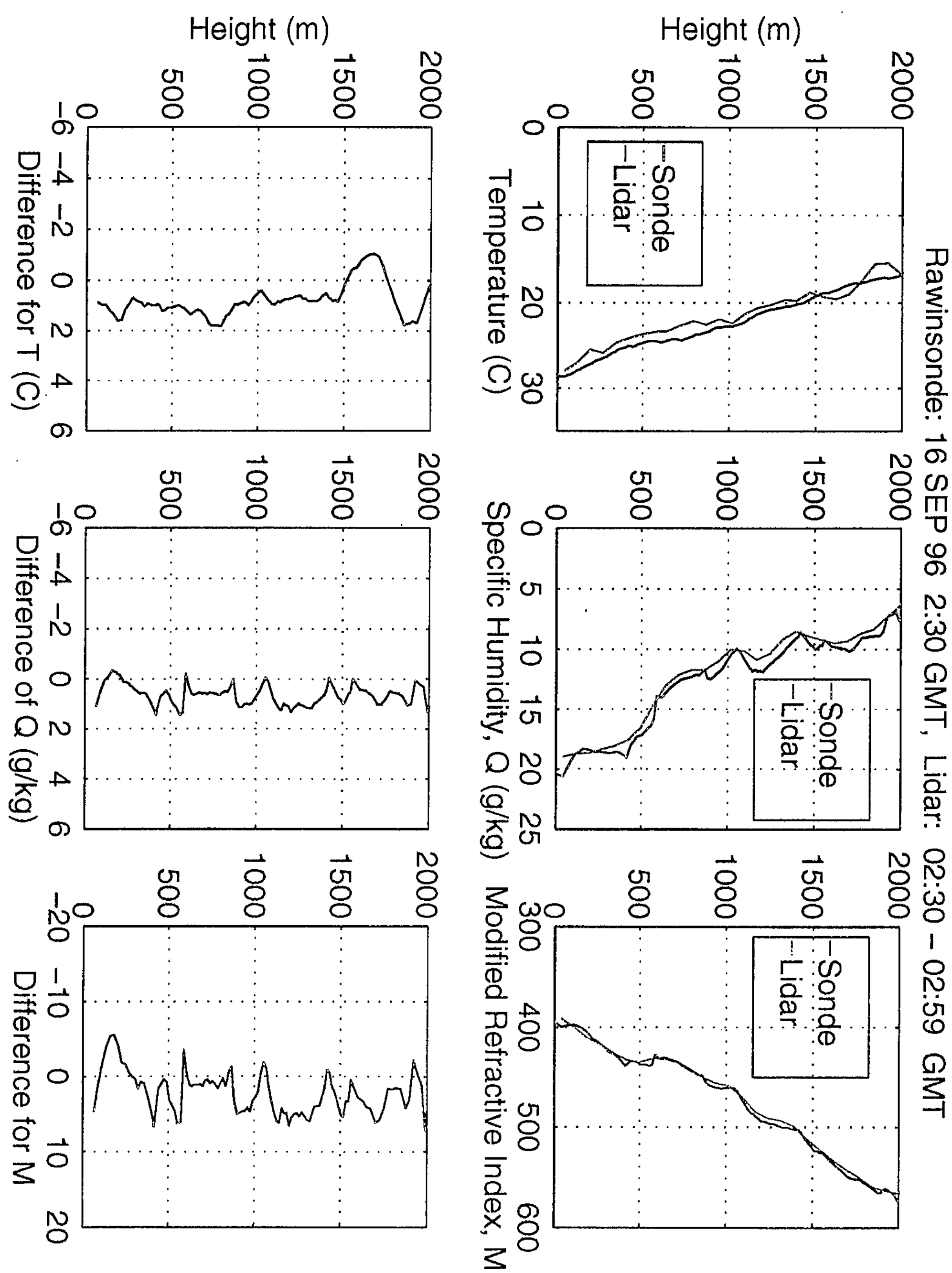

Figure 5.12 Same as Figure 5.3 for 16 Sep 96 data

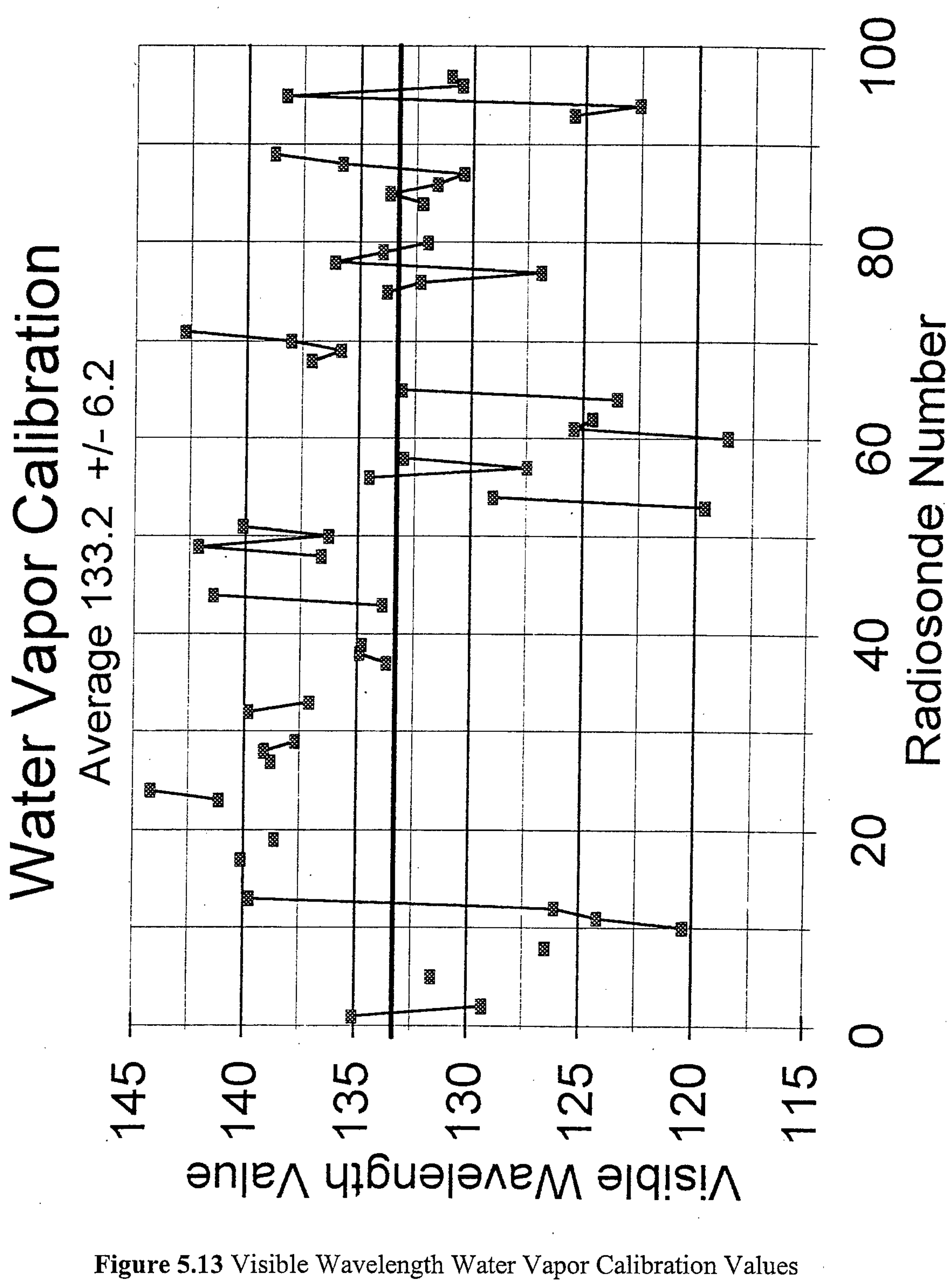

Figure 5.13 Visible Wavelength Water Vapor Calibration Values

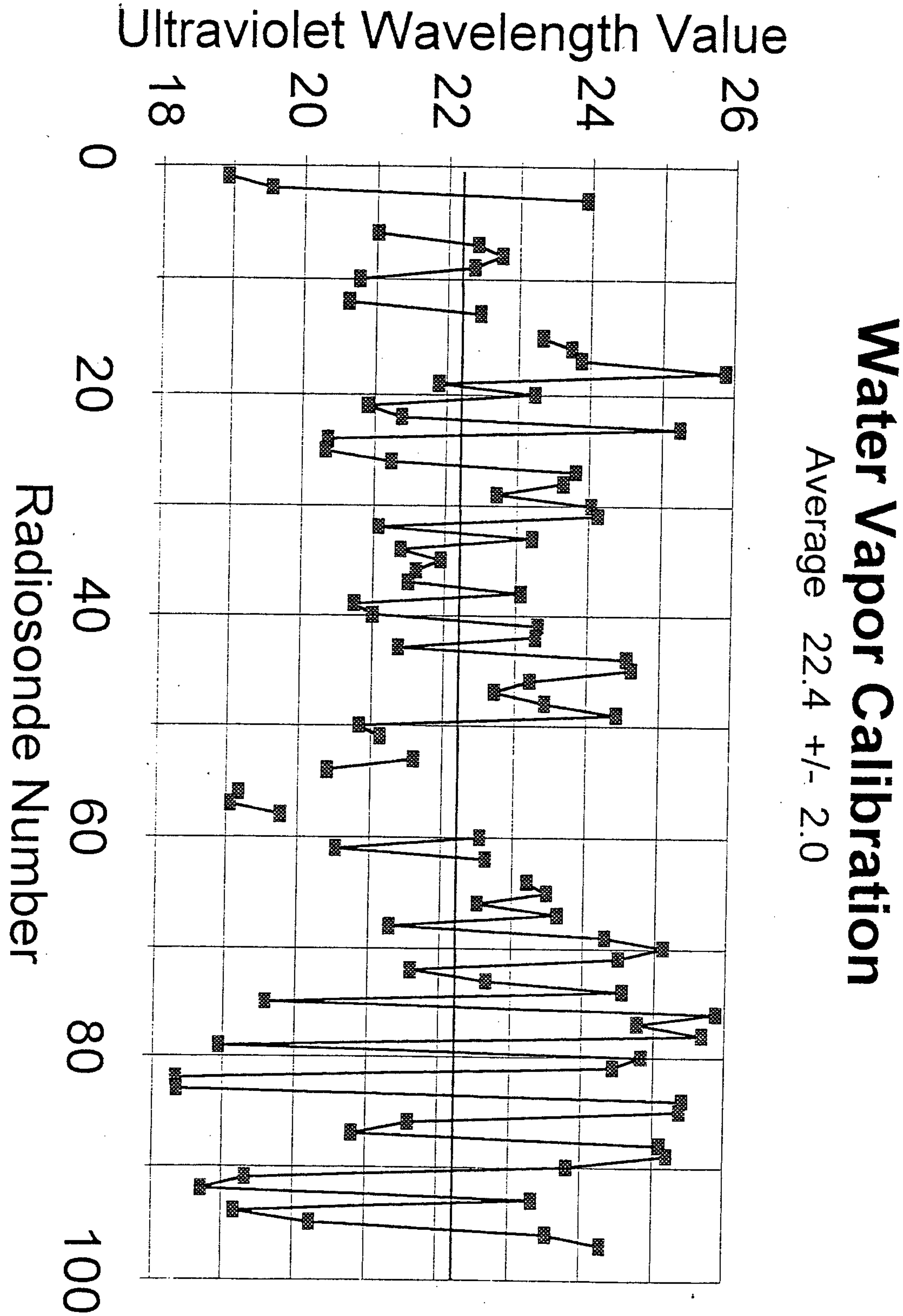

Figure 5.14 Ultraviolet Wavelength Water Vapor Calibration Values

LIST OF REFERENCES

1. Balsiger, F. and Philbrick, R.C., *Comparison of Lidar Water Vapor Measurements using Raman Scatter at 266 nm and 532 nm*, SPIE Vol. 2833 Application of Lidar to Current Atmospheric Topics, 1996.

2. Haris, P.A.T., Stevens, T.D., Maruvada, S. and Philbrick, C.R., *Latitudinal Variation of Middle Atmospheric Density and Temperature*, Advanced Space Res. Vol. 14, pp. 83-87, 1994.

3. Haris, P.A.T., *Pure Rotational Raman Lidar for Temperature Measurements in the Lower Troposphere*, PhD Dissertation, The Pennsylvania State University, 1995.

4. Kunkel, K.E. and Weinman, J.A., *Monte Carlo Analysis of Multiple Scattered Lidar Returns,* Journal of the Atmospheric Sciences, Vol. 33, 1976.

5. Painter, S.S., *Evaluation of Lidar to Support Shipboard Atmospheric Profiling Requirements*, STC Technical Report 4037, 1990.

6. Philbrick, C.R., *Raman Lidar Measurements of Atmospheric Properties*, SPIE Vol. 2222 Atmospheric Propagation and Remote Sensing III, 1994.

7. Philbrick, C.R. and Blood, D.W., *Refractive Propagation Effects Measured by Lidar,* Proceedings of the Beyond Line of Sight Conference (BLOC) at ARL University of Texas Austin, 1994.

8. Philbrick, C.R. and Blood, D.W., *Lidar Measurements of Refractive Propagation Effects,* Propagation Assessment in Coastal Environments, NATO-AGARD CP 567, 1994.

9. Philbrick, C.R., *Lidar Profiles of Atmospheric Structure Properties*, SPIE Vol. 1492 Earth and Atmospheric Remote Sensing, 1991.

10. Philbrick. C.R., Sipler, D.P., Davidson, G., Moskowitz, W.P., *Remote Sensing of Structure Properties in the Middle Atmosphere Using Lidar*, Proceeding of OSA Topical Meeting on Lasers and Remote Sensing, 1987.

11. Rajan, S., Mathur, S.L. and Philbrick, C.R., *Analysis of Atmospheric Water Vapor Measurements Using a Raman Lidar*, Proceedings of the IEEE Topical Symposium on Combined Optical-Microwave Earth and Atmospheric Sensing, 1995.

12. Rajan, S., Kane, T.J. and Philbrick, C.R., *Mulitiple-Wavelength Raman Lidar Measurements of Atmospheric Water Vapor*, Geophys. Res. Let. 21, 1994.

13. Sang Lee, H., Prasad, C.R., Henderson, A.J. and Mathur, S., *A Differential Absorption Lidar for Assessing Radar Propagation Conditions,* Science and Engineering Services, Inc., 1996

14. Senff, C. and Bosenberg, J., *Measurement of Water Vapor Flux Profiles in the Convective Boundary Layer with Lidar and Radar-RASS,* Journal of Atmospheric and Oceanographic Technology, Vol. 11, 1994.

15. Stevens, T.D. and Philbrick, C.R., *Particle Size Distributions and Extinction Determined by a Unique Bistatic Lidar Technique,* International Geoscience and Remote Sensing Symposium, 1996.

INITIAL DISTRIBUTION LIST

		No. Copies
1.	Defense Technical Information Center 8725 John J. Kingman Rd., STE 0944 Ft. Belvoir, VA 22060-6218	2
2.	Dudley Knox Library Naval Postgraduate School 411 Dyer Rd. Monterey, CA 93943-5101	2
3.	Commander Naval Meteorology and Oceanography Command Stennis Space Center, Mississippi 39529-5000	1
4.	Commander Space and Naval Warfare Systems Command (PMW-185) METOC Systems Program Office 4301 Pacific Hwy. San Diego, CA 92110-3127 Attn: CAPT C. Hopkins/S.Payne/Dr. E. Mozley	3
5.	Commander Naval Oceanographic Office 1002 Balch Blvd., Code N14 Stennis Space Center, MS 39522-5001	1
6.	Chief of Naval Research 800 North Quincy Street Arlington, Virginia 22217	1
7.	Naval Air Warfare Center Weapons Division NAWCWPNS, Geophysics Division Code P3542 Point Mugu, CA 93042-5001 Attn: Roger Helvey	1
8.	Johns Hopkins University Applied Physics Lab Laurel Rd. Laurel, MD 20723-6099 Attn: John Rowland	1

9.	Applied Research Laboratory The Pennsylvania State University P.O. Box 30 State College, PA 16804-0030 Attn: Professor Philbrick	2
10.	Aegis Program Manager PMS 400 B30AD Arlington, VA 22242-5186 Attn: Mr. D. Cole	1
11.	Naval Research Laboratory, TOWS Stennis Space Center, Mississippi 39529-4004	1
12.	Oceanographer of the Navy Naval Observatory 34th and Massachusetts Avenue NW Washington DC 20390-5000 Attn: Franceen George	1
13.	Naval Research Laboratory Naval Postgraduate School Annex Monterey, California 93940-5006 Attn: A. Goroch	2
14.	Professor K. Davidson Meteorology Department, Code MR/DS Naval Postgraduate School Monterey, California 93943-5002	3
15.	Professor C. Wash Meteorology Department, Code MR/WX Naval Postgraduate School Monterey, California 93943-5002	2
16.	LCDR Daniel E. Harrison HQ USSPACECOM/J5R 250 S. Peterson Blvd., STE 116 Peterson AFB, CO 80910-3080	1